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LORAD SIGNAL PROCESSING ANALYSES. (U)

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(10) R. K. Betsworth — 2633
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TECHNICAL MEMORANDUM

LORAD SIGNAL PROCESSING ANALYSES

by

R. K. Betsworth

INTRODUCTION

This memorandum describes briefly the laboratory tests conducted to determine the signal processing gain of the present Lorad signal processing equipment (reference Lorad block diagram, March 1961). These tests were by no means comprehensive or exhaustive, but did suffice to demonstrate the processing gain of the system for several independent but similar setups for mixing and measuring input signal and noise. The numerical results obtained from these tests are sufficient to answer some of the initial questions which were raised concerning the signal processing gain of the system and to determine what losses, if any, could be attributed to particular portions of the circuitry included in the tests. This memorandum should not be construed as a report, as its basic function is to provide, for engineering purposes, information associated with the initial Lorad signal processing analyses. This memorandum covers a portion of the work done under AS 02101-5, S-F001 03 02, Task 8016 (NEL E1-3) by Code 2633c.

BACKGROUND

The central portion of the Lorad signal processing system prior to computer data processing is a Multiplex Deltic Correlator[1,2] built by Computer Control Co., Inc., Framingham, Massachusetts. The unit supplies

1. Harvard University Acoustics Research Laboratory TM-37, THE DELTIC CORRELATOR by V. C. Anderson, 5 January 1956
2. Instruction Manual for a Multiplex Deltic Correlator, Vol. 1, Computer Control Company, Inc.

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polarity-coincidence cross-correlation of sixteen simultaneous input signals with eight stored reference signals in all possible combinations once every 5008 microseconds. Each input signal and each reference signal is clipped, translated in frequency, filtered, clipped again, sampled, and then time-compressed prior to being applied to a three phase correlator. The sixteen time-compressed input signals are supplied sequentially for 313 microseconds each to the signal terminal of eight three phase correlators. The entire system, including input bandpass filters and output comb filters, is optimally designed for a 100 cycle per second bandwidth. The Deltic sampling rate is 5008 microseconds and the time compression factor is 15024.

THEORETICAL PROCESSING GAIN

The signal employed by Lorad is pseudo-noise generated by a digital shift register driven by a precision oscillator. The received signal is processed by cross-correlating it with a stored replica (reference) of the transmitted pulse. A signal appears at the correlator output when the received signal "matches" the stored replica. The output signal-to-noise ratio for small values of signal-to-noise ratio at the input is given in the following equation[3]

$$(S/N)_{out} = (S/N)_{in}\, T\Delta f \qquad (1)$$

where

$(S/N)_{out}$ = ratio of peak signal power to noise power at correlator output.

3. Harvard University Acoustics Research Laboratory, TM-27, Correlators for Signal Reception, by J. J. Faran, Jr, and R. Hills, Jr., 15 Sept. 1952

$(S/N)_{in}$ = ratio of signal power to noise power at correlator input

T = integration time of correlator output filter

f = bandwidth of signal at correlator input

The parameters chosen for the developmental Lorad equipment are:

T = 313 microseconds; Δf = 1.5024 megacycles

Substituting these in equation (1),

$$(S/N)_{out} = (S/N)_{in}(313)\,(1.5024)$$

or

$$\frac{(S/N)_{out}}{(S/N)_{in}} = 27 \text{ db} \qquad \text{theoretical processing gain.}$$

Thus, for an input signal-to-noise ratio of -27 db, the peak signal/rms noise ratio at the correlator output will be unity. The theoretical processing gain response curve is plotted in fig. 1.

LABORATORY PROCESSING GAIN MEASUREMENTS

Laboratory measurements were made to determine processing gain of the Lorad signal processing equipment, where

$$(\text{Processing Gain})_{measured} = \left(\frac{\text{peak signal}}{\text{rms noise}}\right)_{out} \text{db} - \left(\frac{\text{rms signal}}{\text{rms noise}}\right)_{in} \text{db.}$$

The initial tests were conducted in September 1961, prior to shipboard installation of the Lorad equipment on the USS BAYA, and included the input transmit/receive bandpass filters, Multiplex Deltic Correlator, comb filters, primary OR and secondary OR circuitry. The test setup is shown in fig. 2. The input signal was pseudo-noise from one of the eight range rate reference generators (TP21-28, in Processor Cabinet No. 2), depending

on the reference channel to be tested. This signal was mixed with band limited thermal noise from a General Radio Noise Generator, Model 1390B, and fed into the selected signal channel to be tested via its input bandpass filter. The bandpass filter input was made available through a beam test box permanently located on the filter cabinet. Noise of sufficient amplitude to control the clipper amplifiers in the Deltic cabinet was fed to the other 15 signal channels via their associated input bandpass filters to simulate sea noise conditions and to eliminate any cross-talk effects that might influence the processing gain measurements. Input signal and noise levels were measured at the clipper amplifier input (bandpass filter output) in the Deltic cabinet using a HP 400-C vacuum tube voltmeter to monitor the clipper amplifier side of a low pass RC filter which was installed on the clipper cards to reduce system noise. Nominal level of the injected thermal noise was 30 db above system noise at this point. This procedure was repeated several times to include different combinations of signal and reference channels in the tests.

The output noise level was measured at the center tooth of the comb filter associated with the reference channel being tested. This level was measured during periods when no correlation functions existed using a HP400-D vacuum tube voltmeter. To prevent capacitive loading of the 1.5 megacycle signal at this point, a 40 db resistive pad was installed on the filter tooth and a short coaxial lead was brought off to the meter.

To provide display persistence of peak output signal, a Hughes 5" Memoscope was used for monitoring purposes. Because of the bandwidth limitations of the Memoscope, the output signal was measured at the dc

amplifier output (TP-1, Processor No. 1) following the secondary OR circuit and was referred back to the comb filter tooth by means of a calibration curve (fig. 3) relating peak signal amplitude at the dc amplifier output to peak signal amplitude at the comb filter output.

Initially, 22 consecutive correlation samples on each of the three input frequencies were recorded for a given input signal-to-noise ratio. From these results, it was determined that if only 12 consecutive samples on each of the three input frequencies were taken, a maximum deviation of 0.2 db in the measured average output signal level resulted. To minimize the time required for running all of the tests desired during a limited time schedule, it was decided that a total of 36 consecutive samples (12 for each frequency band) would be sufficient for determining the processing gain of a channel at a given input signal-to-noise ratio.

Due to the combined background noise peaks from all eight of the reference channels at the secondary OR circuit output, the minimum input signal-to-noise ratio for 50% detectability of the correlation function at the output monitor was -4 db. For all correlation functions not seen at the output monitor, the signal level was recorded as being equal to one-half of the average rectified level because of the probability that the correlation function, not detectible at this point, could have an amplitude of zero or an amplitude equal to the peak noise background.

From the test results, tabulated in Table 1, the average processing gain of the system was about 21 db. In some of the test configurations for an input signal-to-noise ratio of -4 db, sufficient correlation

TABLE 1. Processing Gain
(normal operation)

$(S/N)_{in}$ db	Processing Gain db									
*	S3,R1	S3,R2	S3,R3	S3,R4	S3,R5	S3,R6	S3,R7	S3,R8	S9,R5	S14,R5
0	16.3	16.0	17.7	18.3	17.9	18.1	18.3	18.2	16.5	16.3
-2	18.2	18.0	19.6	19.9	19.1	--	--	--	18.2	17.7
-4	--	20.0	21.5	21.8	21.0	21.0	20.8	21.5	--	--
note 1	19.9	19.9	20.1	21.8	20.6	20.8	21.2	20.6	20.0	18.7

* S = signal channel (1 of 16 beams)
R = reference channel (1 of 8 range rates)

note 1: $(S/N)_{out}$ for no noise in

functions were not detectible to compute processing gain. Because of the time element involved, all test configurations were not run for the condition where the input signal-to-noise ratio was -2 db. One can best understand the reason for an increase in processing gain as the input signal-to-noise decreases by observing figure 1, where the theoretical processing gain response curve has been plotted. Here it is seen as the input signal-to-noise ratio decreases the system is operating on the linear portion of the response curve.

From the test results and equation 1, there is a 6 db negative deviation from the maximum theoretical processing gain. In an attempt to determine where the losses occurred in the system, several additional tests were performed. One of these tests was to repeat the above procedure but using the permanently installed 30 cps input bandpass filters in reference channel No. 5 instead of the normally used 100 cps bandpass filters. From the limited data obtained (Table 2), the results were inconclusive. Theoretically, for the 30 cps case, the processing gain should decrease by a factor equal to the ratio of the bandwidths less the increase in gain due to a higher sampling rate; however, the results indicated there was no difference between the two operating conditions.

To eliminate the skirt effects of the input bandpass filters in the system, another test was performed, whereby pre-filtering by means of a steep-sided 1000-1100 cps bandpass filter was used in signal channel no. 3 and reference channel no. 5 (fig. 4). The output of the special filter was then heterodyned up to the frequency band A, B, or

TABLE 2. Processing Gain
(100 cps bandwidth versus 30 cps bandwidth using signal channel 3 and reference channel 5)

$(S/N)_{in}$ db	Processing Gain db	
	BW = 100 cps	BW = 30 cps
+4	14.8	15.5
0	17.9	18.0
-2	19.1	19.0
-4	21.0	20.9
note 1	20.6	20.2

note 1: $(S/N)_{out}$ for no noise in.

C, and fed into the normally used bandpass filters in the two channels where the unwanted side band was rejected. The results of this test are shown in table 3. An additional test to eliminate the input bandpass filters completely was performed using the scheme shown in fig. 5. The bandpass filters and frequency translation circuitry were bypassed and a 50 cps tonal signal was mixed with pre-filtered thermal noise and fed directly into the clipper amplifiers preceding the Deltic storage lines (Note: Initially an alternative method was suggested whereby the reference Deltic was stored with all zeroes and cross-correlated with a 100 cps tonal input signal on the corresponding signal Deltic. However, one does not get the true picture in this case due to the superposition of the two sidebands at the comb filter which results in a voltage gain of 6 db). The results of these tests indicated there was negligible loss associated with the input bandpass filters.

During a two week period in January 1962, in which the USS BAYA was tied up at the NEL pier, a series of shipboard laboratory tests was performed to determine the processing gain of the same Lorad signal processing equipment, excluding any effects of the primary OR and secondary OR circuitry during the measurements. These tests were conducted to verify previous results, isolate losses, and to obtain a processing gain figure for a lower input signal-to-noise ratio. (Bypassing the OR circuitry decreases the number of background noise peaks and allows detection of the correlation function for smaller values of input signal-to-noise ratio). Techniques used in the initial

TABLE 3. Processing Gain
(Prefiltered signal versus normal bandpass filters using signal channel 3 and reference channel 5)

$(S/N)_{in}$ db	Processing Gain db	
	Pre-filter	Normal
0	17.0	18.0
-4	20.4	20.9
note 1	20.7	20.7

Note 1: $(S/N)_{out}$ for no noise in

tests were repeated here for mixing signal and noise and feeding it into the system. Because of the processing gain uniformity obtained for various combinations of signal and reference channels in the initial tests, and time schedule limitations, only signal channel no. 3 and reference channel no. 5 were used in these tests. All output measurements were made at the center tooth of the comb filter. A buffer amplifier, fig. 6, providing proper termination of the comb filter tooth and isolation to prevent loading of the 1.5 megacycle signal at this point was installed on the filter output terminal. To provide display persistence of the correlation function for measurement purposes, the Memoscope was used for monitoring the peak output signal. Because of the bandwidth limitations of the Memoscope, an envelope detector was required to detect the 3 kilocycle per second correlation function. Necessary precautions were taken to insure the correlation function was centered in the filter (tooth 17) being monitored. A response curve was run on the peak detector circuitry to determine its loss (0.3 volts peak) and this result was added to the peak output signal level.

As in the previous tests, pre-filtered thermal noise of sufficient amplitude to control the clipper amplifiers in the Deltic was fed to the 15 input signal channels not under test. Once the test commenced, consecutive correlation function amplitudes were recorded. The total number of samples taken at a given input signal-to-noise ratio was 36; 12 for each of the three frequency bands. Because of the probability that the signal missed could equal zero volts or be equal to the peak

noise background, all correlation functions not detected were recorded as being equal to one-half of the average rectified level at the output monitor. This series of tests was divided into four phases and the measured processing gain versus input signal-to-noise ratios are shown in table 4:

Phase 1. The pseudo-noise signal was mixed with thermal noise and fed into input signal channel no. 3 via its input bandpass filter. The block diagram of the test setup for phases 1 and 2 is shown in figure 7.

Phase 2. To determine if there was processing loss associated with the multiplexing portion of the Deltic, the tests of phase 1 were repeated with the multiplexing circuitry disabled in such a manner that only signal input channel no. 3 was operative.

Phase 3. In this test, both the multiplexing and the frequency translation circuitry in the system was disabled. A 50 cps sinusoidal signal from a GR Interpolation Oscillator, type 1107-A, was gated directly into reference Deltic storage line no. 5 via its clipper amplifier. The same 50 cps tonal signal was mixed with thermal noise and fed to the clipper amplifier which gates information directly into signal Deltic storage line no. 3 (fig. 8). The frequency of the oscillator was adjusted to insure that the correlator output signal came through the center of the comb filter tooth that was monitored. To measure the output noise level at the comb filter tooth, the tonal signal was turned off. The same output noise level was obtained by changing the oscillator frequency to shift the tonal signal off the monitored filter tooth. Due to the

TABLE 4. Processing Gain
(test conducted in January 1962 using signal channel 3, reference channel 5, and 100 cps bandwidth)

$(S/N)_{in}$ db	Processing Gain db					
	Phase 1	Phase 2	Phase 3	Phase 4	Initial Test	Mean
0	19.0	17.2	17.7	18.1	17.9	18.0
-2	20.2	18.7	18.9	20.7	19.1	19.5
-4	20.9	19.7	19.6	21.6	21.0	20.6
-6	21.2	20.3	20.3	22.8	-	21.2
note 1	21.8	21.2	22.8	20.3	20.6	21.3

note 1. $(S/N)_{out}$ for no noise in

Phase 1. Normal Operation
Phase 2. No Multiplexing
Phase 3. No Multiplexing, No Translation
Phase 4. No Translation

difficulty associated with centering the tonal signal in the tooth, the former method was used throughout the test for measuring the output noise level.

Phase 4: The Deltic multiplexing circuitry was enabled for normal operation (sequential sampling of the 16 signal channels). The frequency translation remained disabled and the tests of phase 3 were repeated.

Also shown in table 4, for comparative purposes, are the results of the initial test for signal channel no. 3 and reference channel no. 5, where the signal was measured at the OR circuit output and referred back to the comb filter. These results are included in the computations of the mean processing gain shown in the table.

RESULTS

In all of the test phases, the minimum input signal-to-noise ratio for 50% detectibility was -8 db and the measured processing gain was about 21 db. Processing gain was not computed where the input signal-to-noise ratio was -8 db because the amplitude of the correlation function could not be measured accurately for this test condition. Deviations from the mean processing gain of 21 db can be partly attributed to some drift in the Memoscope and interpretation of the mean output noise level due to the damping factor of the vacuum tube voltmeter used in the tests. The maximum deviation of ± 1.2 db can be attributed to measurement error, which is not unreasonable for test conditions of this nature. The increase in signal processing gain as input signal-to-noise ratio decreases can best be understood by observing fig. 1 where the mean processing gain response

curve is plotted from the data tabulated in table 4. Here one realizes that as input signal-to-noise ratio decreases the system is operating on the linear portion of the response curve. The measured recognition differential[4] (output signal-to-noise ratio for 50% detectability) was 13 db. Theoretically, for small values of input signal-to-noise ratio, the processing gain at the comb filter output would be 27 db; of course, this figure cannot be achieved due to system losses.[5,6] With independent, but similar, setups for mixing and measuring input signal and noise, there was no significant difference between the signal processing gain obtained in the September 1961 and the January 1962 tests.

CONCLUSIONS:

1. The measured signal processing gain of the present Lorad signal processing equipment, excluding the effects of the OR circuitry, is 21 db, which is 6 db less than the theoretical figure of 27 db. In discussing this loss with others in the field, it appears that a large part of the 6 db deviation from the theoretical maximum processing gain can be attributed to the combined losses of signal clipping and sampling rate. The theoretical calculations of the individual losses associated with clipping and sampling do not approach 6 db; however, in tests performed by Code 2354 on similar signal processing equipment, using polarity-coincidence cross-correlation techniques and having a theoretical processing

4. A Summary of Underwater Acoustical Data, Part III, "Recognition Differential", Urich and Pyrce, ONR, December 1953
5. Faran and Hills, op. cit.
6. Anderson, op. cit.

gain of 27 db, a 3 db increase in the measured processing gain resulted when the sampling rate was doubled. Prior to doubling the sampling rate, a measured processing gain of 21 db was obtained.

2. The measured recognition differential when the signal is viewed at the comb filter output is 13 db, corresponding to an input signal-to-noise ratio of -8 db. Although no attempt was made to determine the false alarm rate in the tests conducted, it was very low.

3. There are no measurable losses associated with the system input band-pass filters, multiplex unit, or the frequency translation circuitry.

4. There is a 4 db loss in detection capability at the secondary OR output due to the combined background noise peaks of the correlator's output. This means that the useful processing gain of the overall signal processing equipment is 21 - 4 = 17 db at the secondary OR output.

5. The minimum usable input signal-to-noise ratio for 50% detection of the signal at the secondary OR output is -4 db.

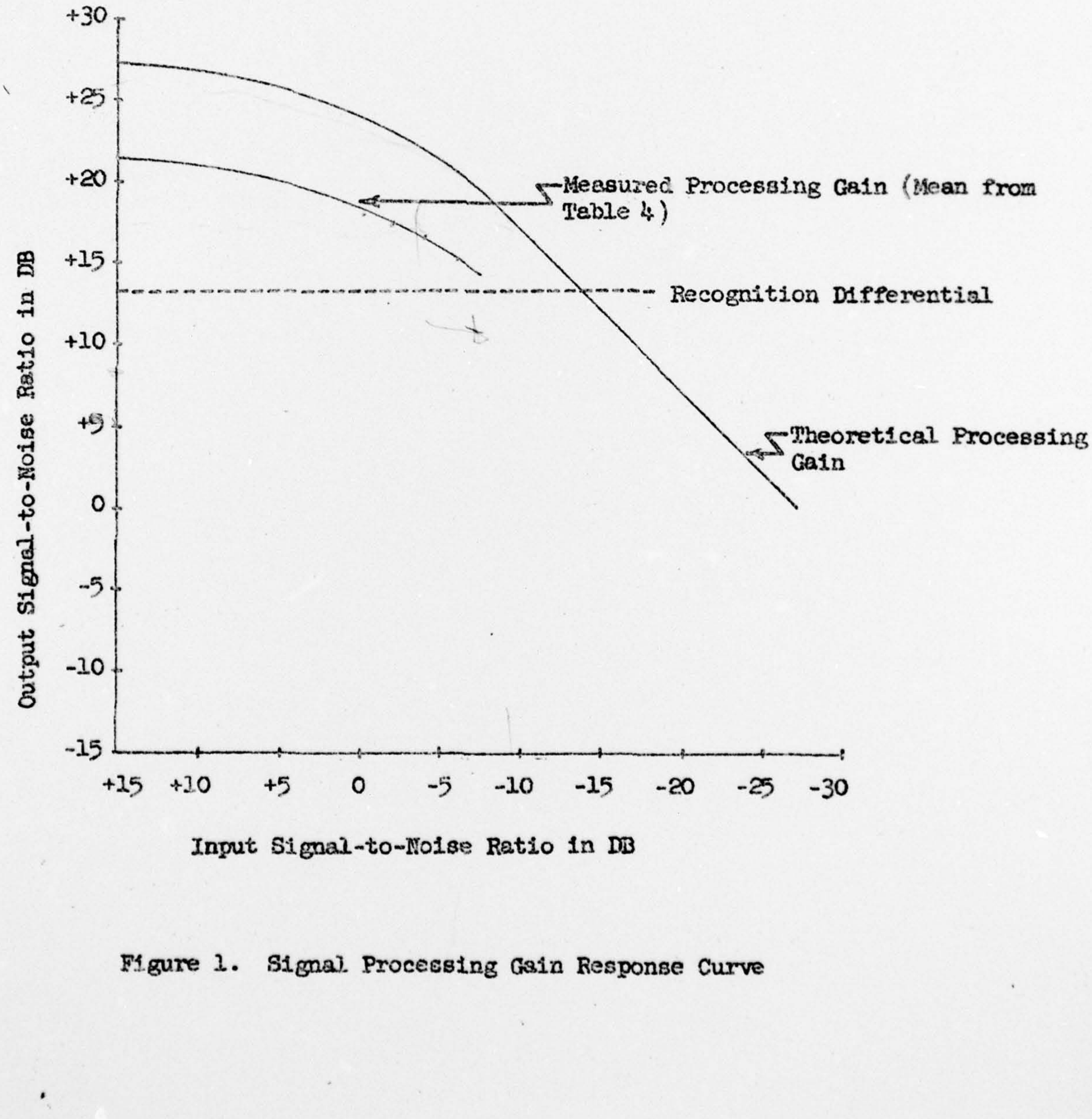

Figure 1. Signal Processing Gain Response Curve

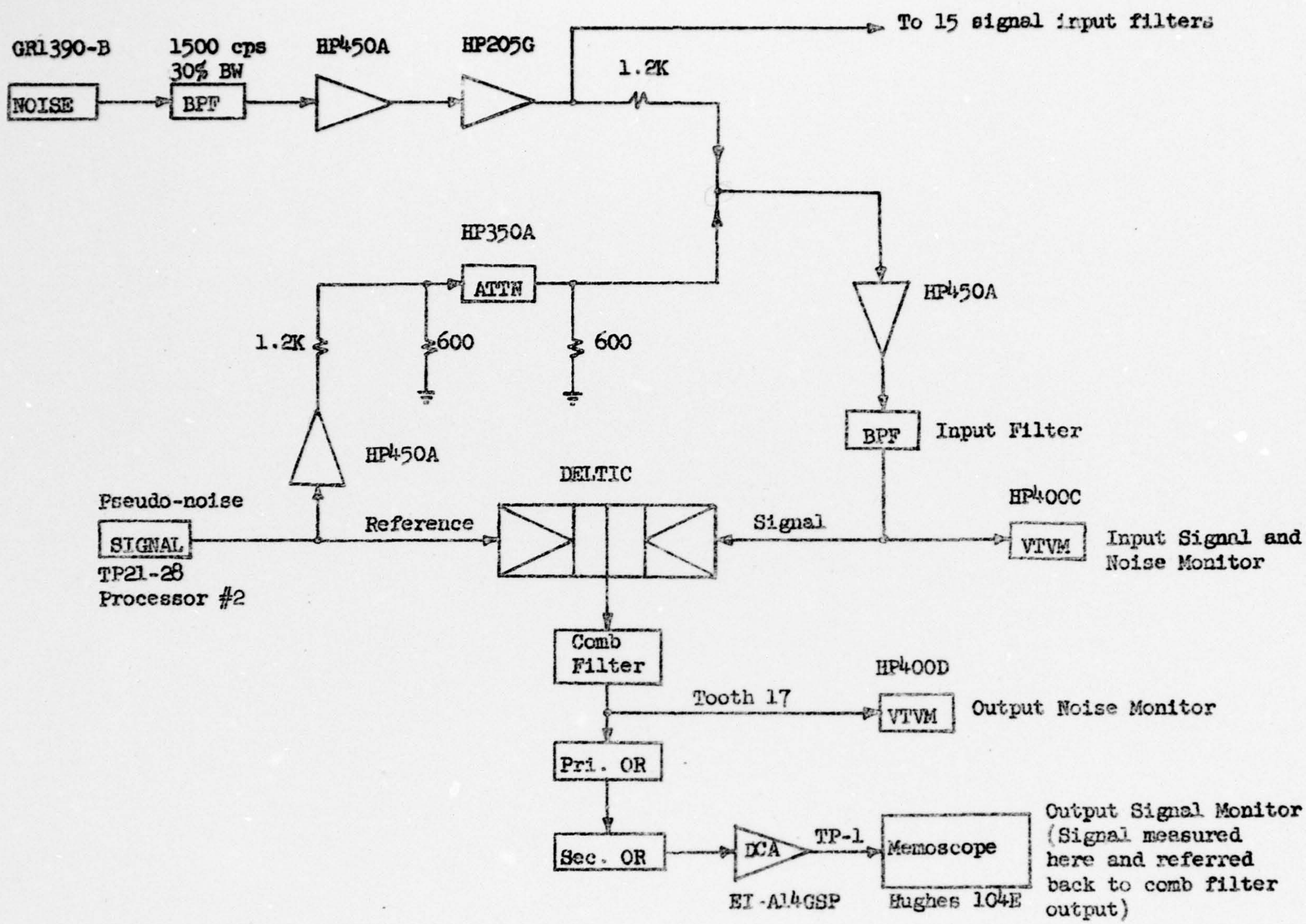

Figure 2. Test Setup for Initial Signal Processing Analyses

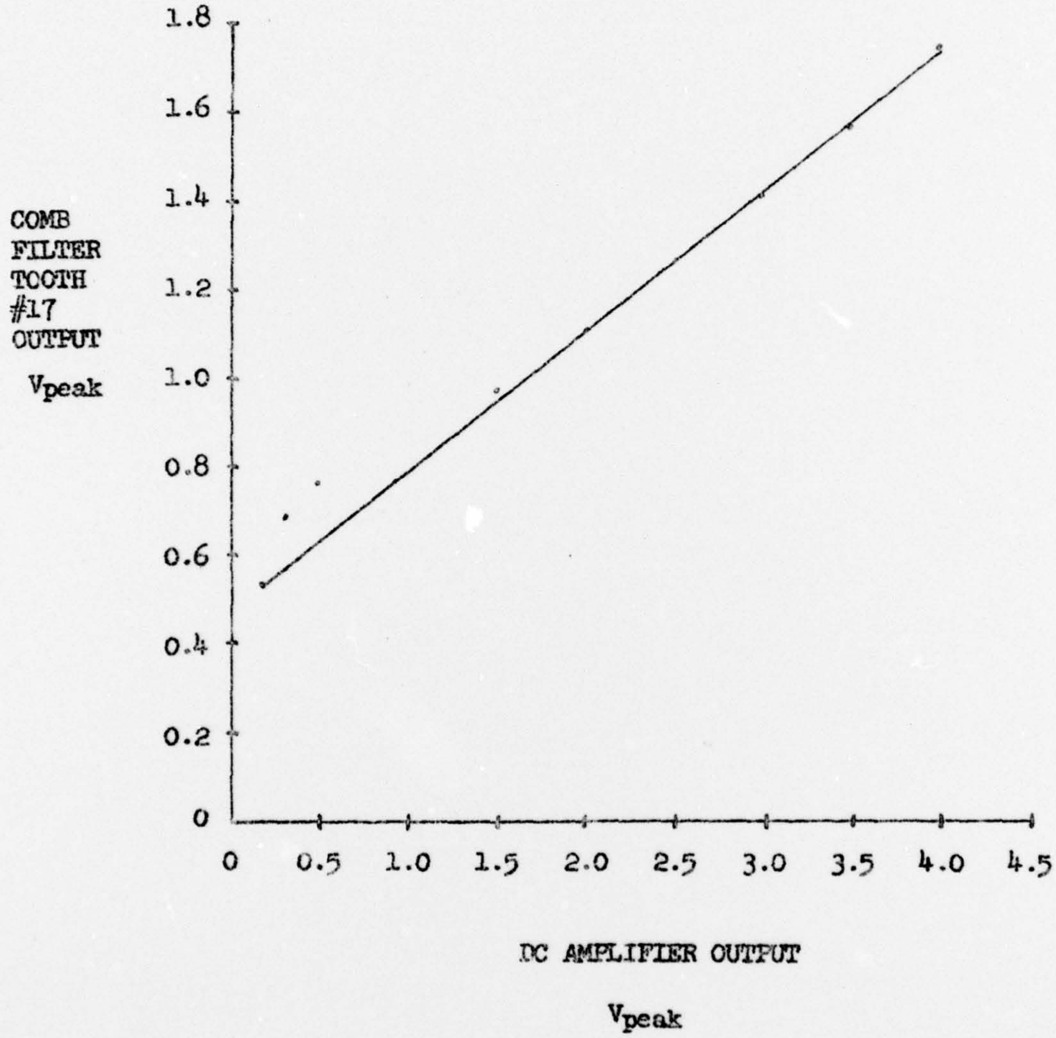

Figure 3. Calibration Curve Relating Peak Signal Amplitude at the Comb Filter Tooth to Peak Signal Amplitude at the DC Amplifier Output

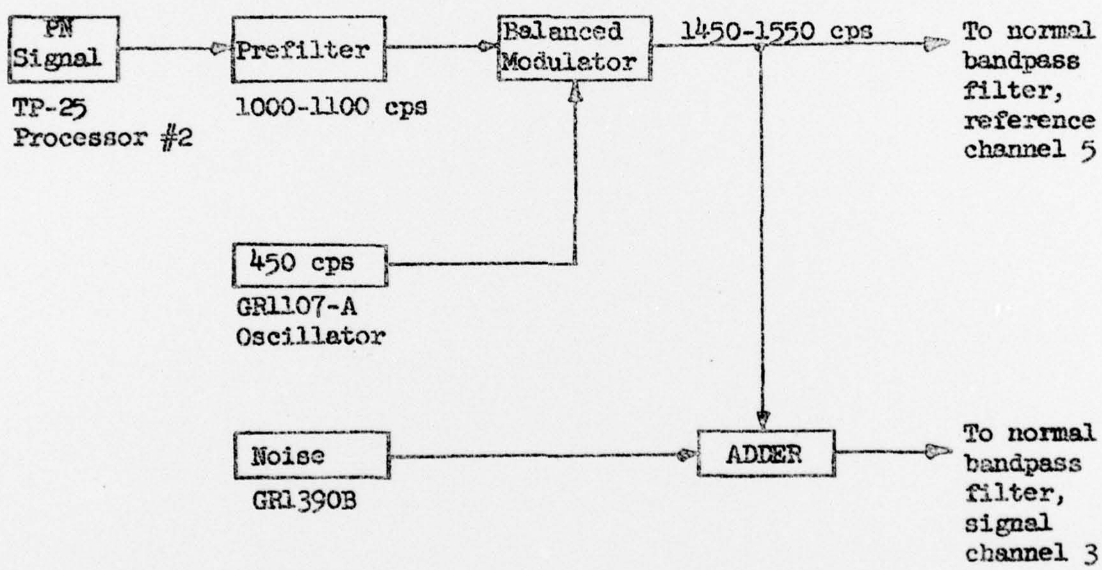

Figure 4. Test Setup to Check Skirt Effects of the Input Bandpass Filters

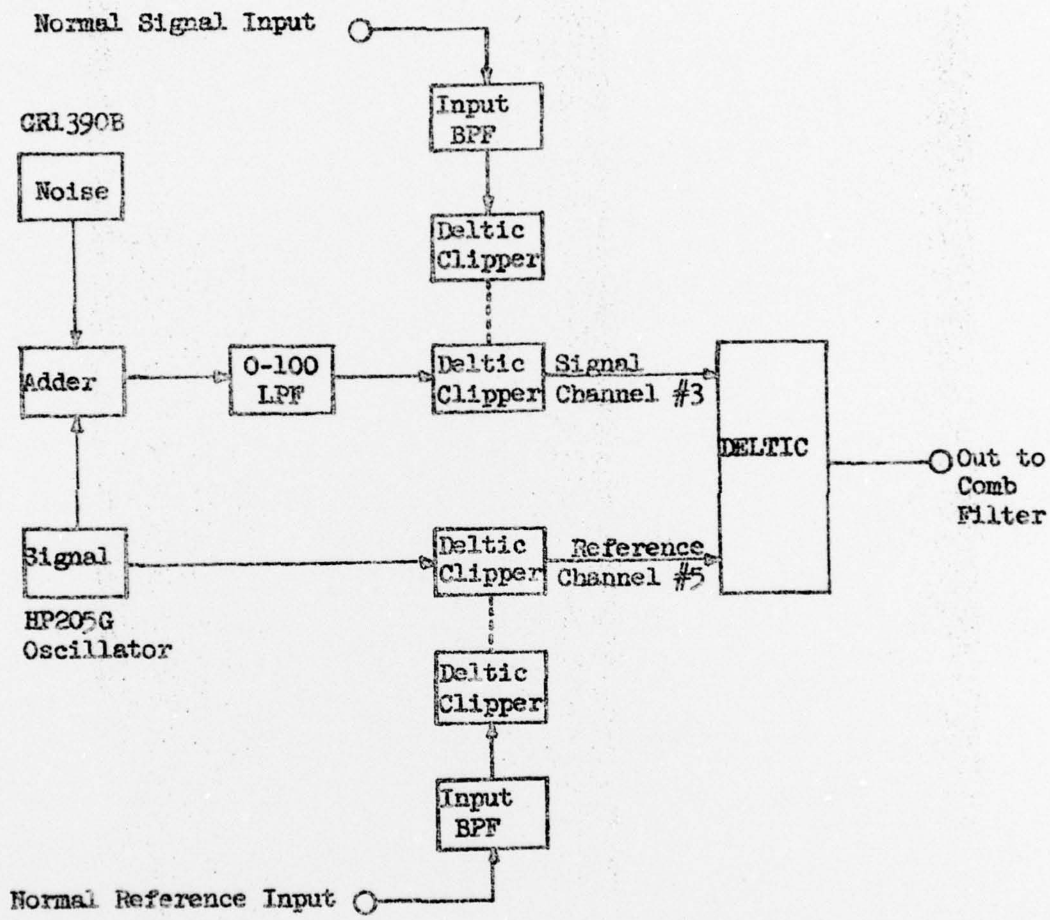

Figure 5. Test Setup to Eliminate the Input Bandpass Filters in the Processing Gain Analyses

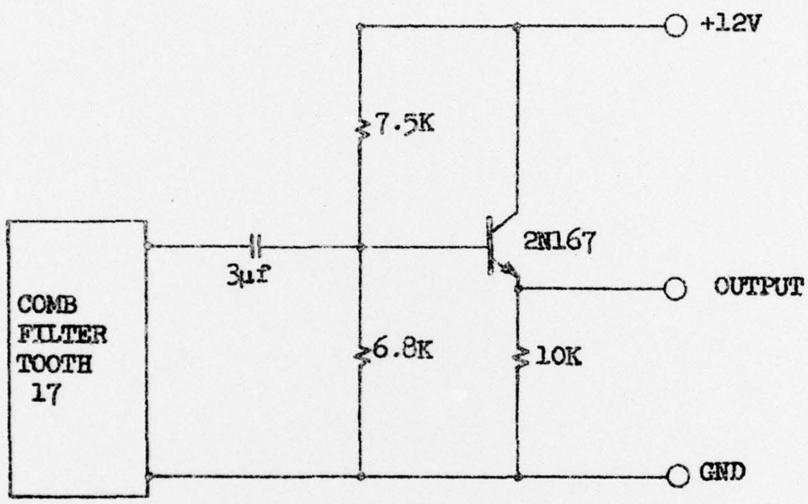

Figure 6. Comb Filter Buffer

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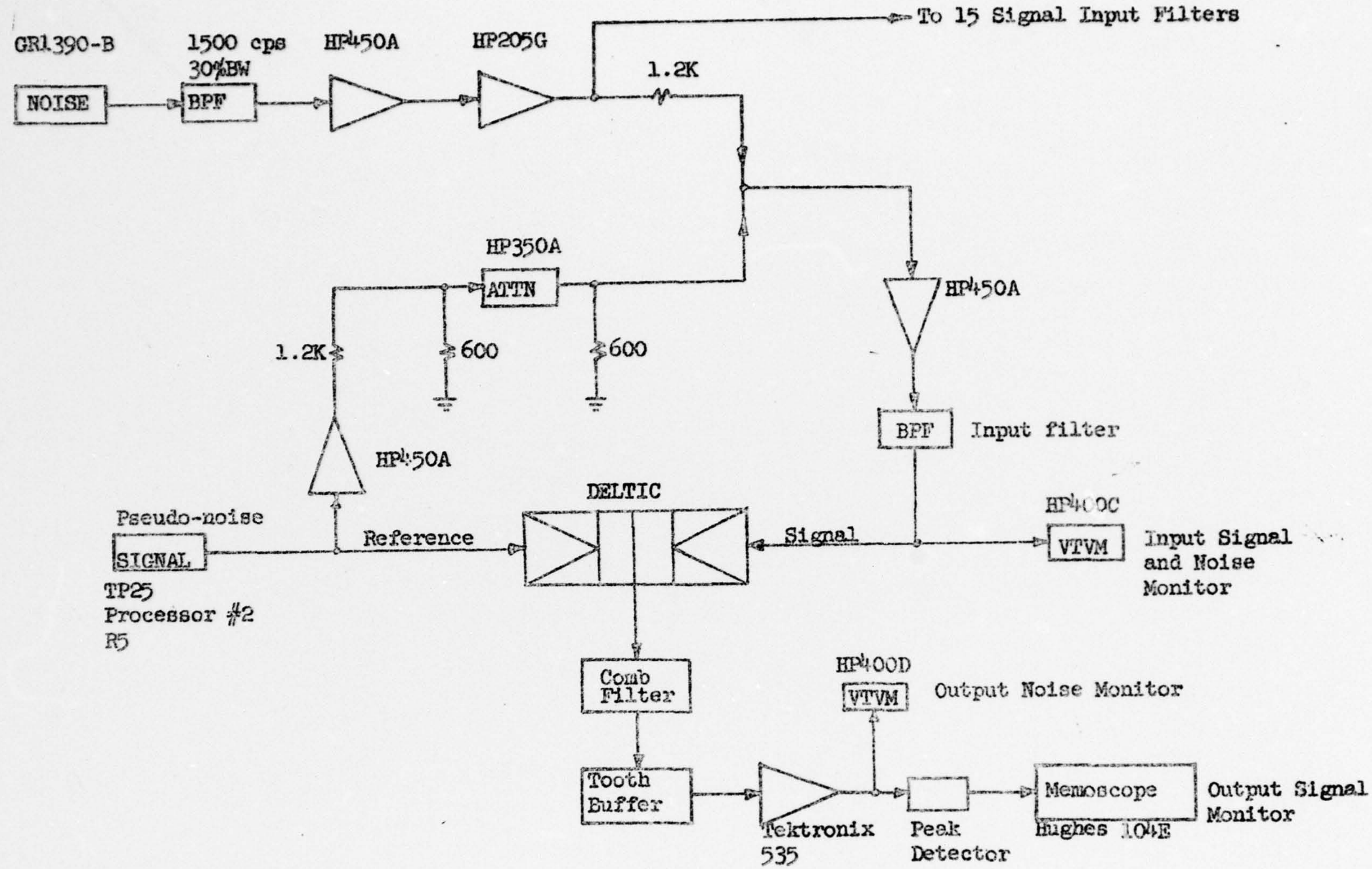

Figure 7. Test Setup for Phase 1 and Phase 2 Signal Processing Analyses

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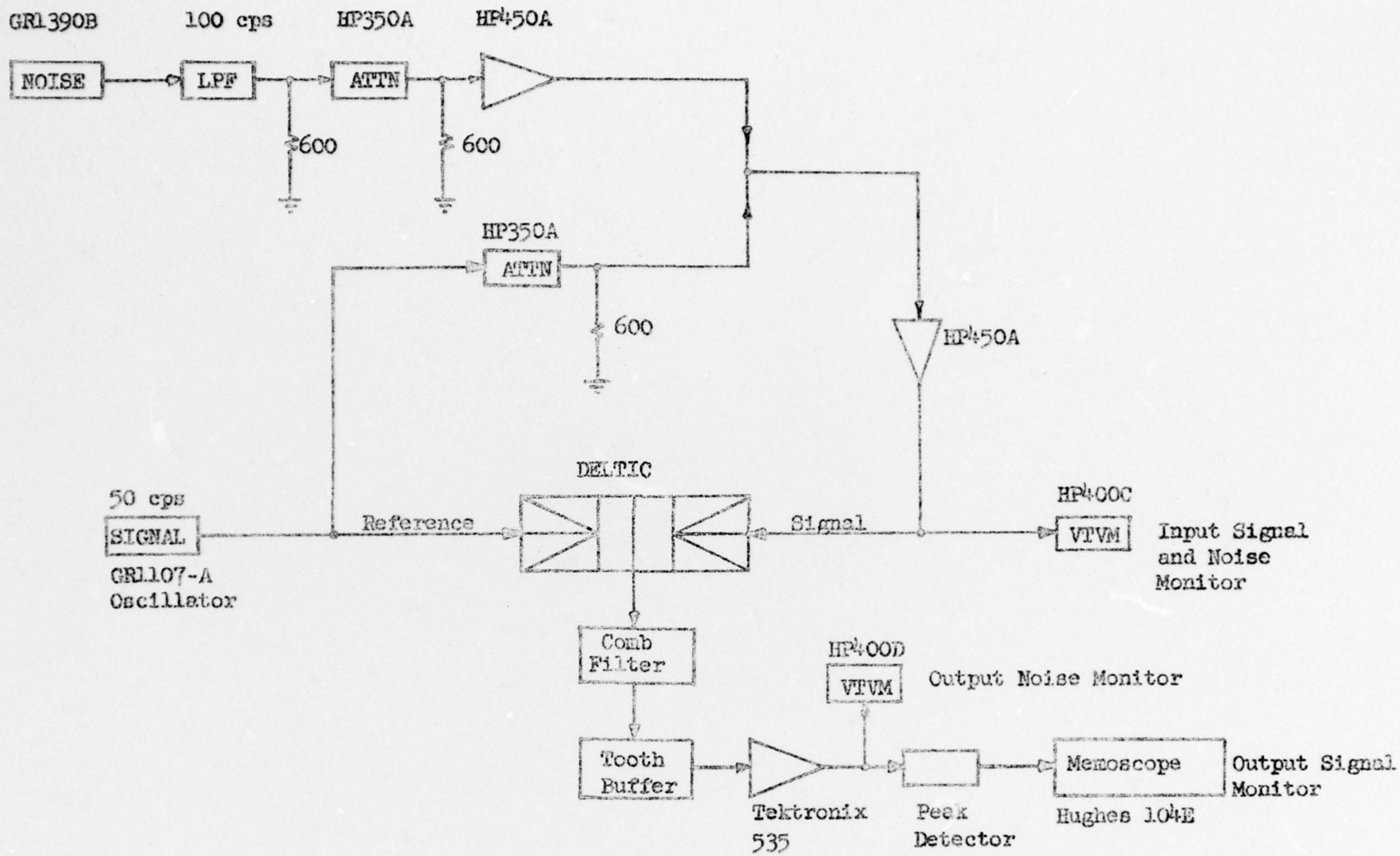

Figure 8. Test Setup for Phase 3 and Phase 4 Signal Processing Analyses

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